

THE CALTECH MILLIMETER WAVE INTERFEROMETER.

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ABSTRACT

The Caltech Millimeter-Wave Interferometer has recently begun observations at a wavelength of 2.6 mm. We describe the instrument and some of the first results from it.

1. Introduction

The techniques of millimeter-wave astronomy have been enormously successful in probing the cold clouds of molecular gas in the interstellar medium. While good information is available on the constituents of such clouds, their physical properties, and their large-scale structures, the early single dishes with resolution $\sim 1'$ were unable to resolve structures smaller than ~ 0.15 pc at a typical distance of 500 pc. The pioneering work of the UC Berkeley interferometer at Hat Creek (c.f., Plambeck et al. 1982; Vogel et al. 1984; contributions in this volume and refs. therein) showed that compact structures exist in OMC1 and other molecular clouds.

The Caltech millimeter-wave interferometer is designed to make high-resolution ($1'' - 10''$) maps of line and continuum emission in the range from 1 - 3 mm. Although these objectives could be approached with a large single dish, interferometers have several advantages:

1. High spatial resolution. Single dishes now under construction may have beam widths as small as $10''$, but this is not easily achieved and puts severe demands on dish pointing. The maximum angular resolution of interferometers is limited by atmospheric effects and should be $\lesssim 0.5''$ (Bieging et al. 1984).
2. Accurate position measurements. The accuracy of interferometric positions is limited by calibration errors rather than by dish pointing and is typically better than 10% of the synthesized beam width.
3. Spatial frequency discrimination. Interferometers can measure emission from compact structures even in the presence of bright, extended emission.
4. High stability. Interferometers inherently reject drifts in system temperature and atmospheric emission, permitting very long integrations to detect weak continuum emission.

This paper describes the Caltech millimeter-wave interferometer which is located in the Owens Valley in California at a latitude of 37° . The elevation is 1200m, and the climate is dry, permitting operation at wavelengths as short as 1 mm in winter. The first CO line measurements at 2.6 mm wavelength were made by the interferometer in late 1982, although continuum work had started earlier. In the winter of 1982 - 83, the first two dishes were used as a single baseline interferometer, with operations up to 50m E - W. During 1983, the third dish was

brought on line, and many parts of the system were changed to allow for 3 baseline operation. Continuum observations were restarted at the end of 1983, and spectral line work commenced in the spring of 1984. By mid-1984, the interferometer was essentially complete, although work is still in progress to expand the maximum baseline from 100m to 400m and to increase the range of spectrometers. Work is also planned to improve the phase stability of the system, and a development program is under way to equip the interferometer with receivers for 1.3 mm.

2. Dishes and Track

The interferometer uses three dishes of 10.4m diameter (Leighton 1978). These dishes have surface errors $\leq 60 \mu\text{m}$ r.m.s. and it is expected that the surfaces will be improved by resetting the panels on the basis of holographic measurements. The dishes are usable to the site limit of 1 mm wavelength, with measured aperture efficiencies of 50% at 2.6 mm and 30% at 1.3 mm. The blind pointing error is ~ 0.1 arcmin r.m.s. Most of this error is due to thermal effects, since the dishes are largely unprotected from sunlight.

The dishes are moveable along a track which has the form of an inverted T (Fig. 1). The eventual length of the north arm will be 400m, with the east and west arms each extending to 200m from the central pad. The maximum baseline of 400m corresponds to a synthesized beam width of $\sim 1''$ at 2.6mm and $0.5''$ at 1.3mm. The basic spacing increment is 10m, but a station at 65m W provides for 5m increments in cases where grating sidelobes are important.

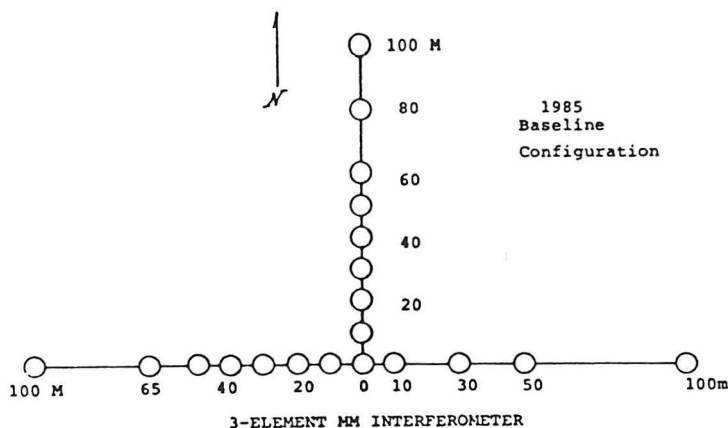


Fig. 1--1985 Baseline Configuration. The baseline will eventually be extended to 200m E, 200m W, and 400m N.

The dishes are moved between stations by a separate transporter. A typical reconfiguration, involving moving all the dishes, measuring new pointing constants, establishing delay center, and measuring baselines requires ≤ 12 hours. The setdown error for the dishes is ~ 2 mm, and the astronomical measurements of the baselines are accurate to ~ 0.2 mm. These baseline measurements are limited at present by systematic effects and result in astronomical positional errors of ~ 0.1 times the synthesized beam width. A baseline determination requires about four hours of observing time. The brute-force search of a 60 mm cube to solve for one baseline requires 5 cpu minutes on a VAX 11/750.

3. Receivers and Local Oscillators

Sensitive receivers are important to an interferometer since the surface brightness sensitivity in a map is given approximately by $\Delta T \sim (T_R/50) \times (\vartheta/1'')^{-3/2} \times (10\text{m}/D)^2$, where ΔT is the 1σ noise level, T_R is the SSB receiver temperature, ϑ is the synthesized beam width in arcseconds, and D is the dish diameter in m. This calculation assumes efficiencies and atmospheric opacity appropriate for the Caltech interferometer and also assumes that the observations are made with a 10m spacing increment so that the total integration time is inversely proportional to ϑ . The equation is not valid for $T_R \lesssim 50$ since in that case the atmosphere emission dominates the system noise.

The interferometer is equipped with three SIS receivers (Woody, Miller, and Wengler, 1985), which are cooled to 4.5 K by closed-cycle refrigerators. Typical receiver temperatures are 200K SSB at ~ 3 mm. The receivers are able to tune from 85 - 115 GHz, but the operating frequency of the interferometer is limited by the range of the available local oscillators. A liquid-helium-cooled SIS receiver (Sutton 1983) is used for single-dish observations at 230 GHz.

The local oscillator power for the 3mm receivers is supplied by varactor-tuned Gunn oscillators, which operate in the range 45 - 55 GHz. The output of each oscillator is doubled in frequency and fed to the receiver through a partially reflecting beam splitter. The doubled output is also fed to a harmonic mixer for the phase-lock circuit.

Fig. 2 shows a simplified diagram of the reference and phase lock scheme. The 600 MHz source is phase-locked to the 5 MHz reference from a hydrogen maser. Since this signal is in common to all dishes, phase noise at modulation frequencies ≤ 1 MHz does not affect local interferometry. For VLBI, the 600 MHz source is replaced by a high-quality synthesizer. The 600 MHz signal is fed to the dishes via a line stabilizer, which uses a modulated reflection technique (c.f. Swarup and Yang, 1963) to monitor and compensate for line-length variations. The line stabilizer operates in a closed loop, with the phase error signal being fed back to an electronic phase shifter. At the antenna, the 600 MHz signal is used to lock an 1800MHz cavity oscillator. The signal from this oscillator is then mixed with a signal in the range 80 - 160 MHz, produced by a synthesizer and distributed via the same cable as the 600 MHz signal. The resultant 1880-1960 MHz signal is doubled, producing a signal in the range of 3760-3920 MHz, which is fed to a harmonic mixer. The output from the harmonic mixer, at 601 MHz, is compared with a 601 MHz reference and used to phase lock the Gunn oscillator.

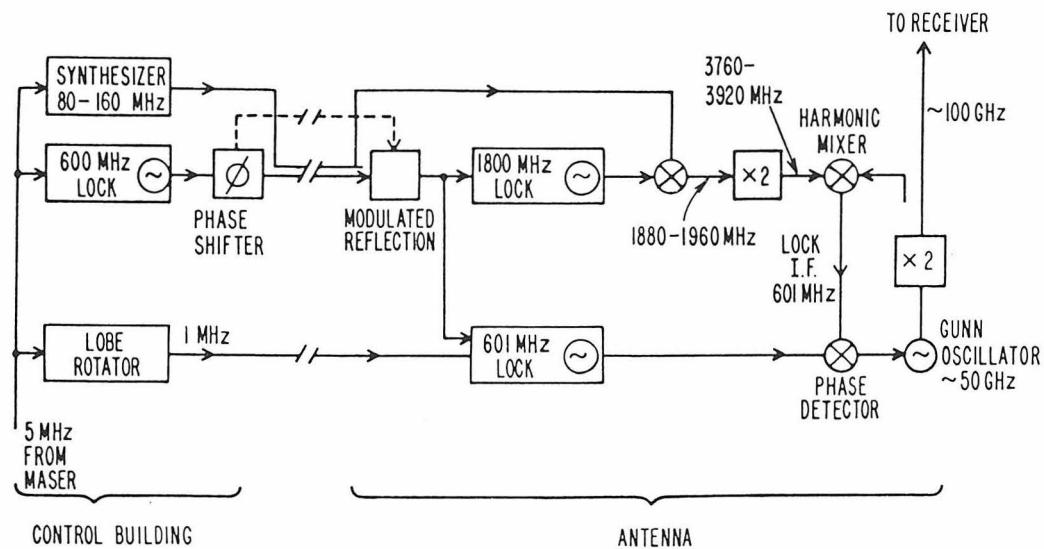


Fig. 2--Local oscillator phase reference system for one antenna.

The 601 MHz reference is derived from the basic 600 MHz signal and a 1 MHz signal, whose phase is controlled by a lobe rotator. The lobe rotator uses a 10-bit ECL counter to produce a phase-shifted signal. The phase and phase rate are determined by rate multipliers. In addition, 180° phase switching is performed. Since phase closure applies, it is necessary to change the phase of only two of the three antennas.

4. Backends

The Caltech interferometer has an analog backend system, using filter spectrometers. This method was chosen on grounds of simplicity and cost. An acousto-optic scheme was considered for the interferometer but was rejected, although acousto-optic spectrometers with bandwidths of 100 MHz and 500 MHz are available for single-dish work (Masson 1982). A diagram of the backend is shown in Fig. 3.

The i.f. signals from the receivers, in the band 1150-1550 MHz, are sent back to the control building and passed through delay lines (one per antenna). The delay lines use a binary sequence of cables, switched by PIN diodes, with a smallest step of 1/32 ns. The delay line temperatures are regulated to ± 0.1 K.

The continuum correlators operate directly at 1350 MHz and use double balanced mixers. An automatic level control system (ALC) is used to avoid problems with non-linearity. Measurements from a total-power detector before the ALC are used to correct the measured fringe amplitudes. Both in-phase (I) and quadrature (Q) correlators are present.

The filter correlators operate at lower frequencies and require one or more extra frequency conversions. I and Q correlators are provided to give the full signal/noise ratio for single sideband signals. A 32 \times 1 MHz bank, covering 83 km/s with 2.6 km/s resolution at 2.6 mm, is available at present. A 32 \times 50 kHz bank is expected to be available in early 1985, with a 32 \times 5 MHz bank planned for late 1985. It will be possible to operate two filter banks simultaneously.

5. Data Sampling

The data taking of the interferometer is done by an LSI-11/03 microcomputer, which performs the phase and delay calculations, controls the lobe rotation and delay lines, and samples and integrates the correlator outputs. A 50/100 Hz, 180° phase switch, which is demodulated in hardware, is used to remove dc offsets. The fringes are stopped by the lobe rotator, and a computer-controlled phase switching cycle is applied. By changing the local oscillator phase through four 90° steps for each baseline, complex fringe amplitudes are measured separately for each I and Q channel. The basic integration period is 0.1 seconds, and a full quadrature cycle requires 0.8 seconds. The raw fringe data are integrated in the computer for a multiple of 0.8 seconds (typically 30 - 60 seconds) to form one record.

Gain and phase corrections for each correlator are applied to yield the complex I and Q fringe amplitudes a_I and a_Q . It was shown by Read (1961) that the I correlator output in a double-sideband interferometer is given by the sum

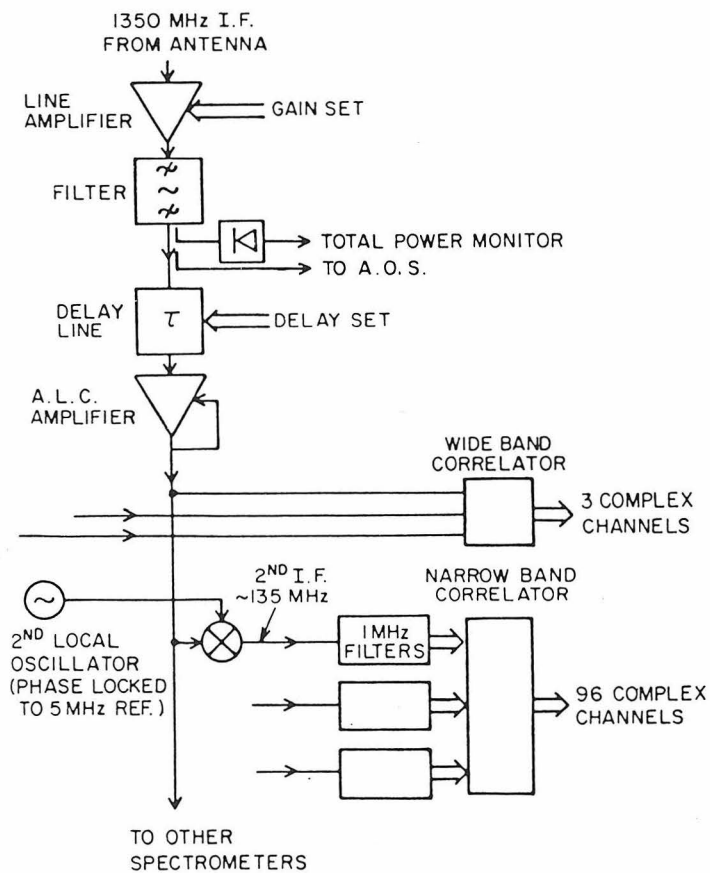


Fig. 3--Interferometer Backend. Amplifier chain is only shown for one antenna.

of a_U and a_L , where a_U and a_L are the complex fringe amplitudes for the upper and lower sidebands respectively. The Q output is given by their difference, with a 90° phase shift. If $a_U = a_L$, and the delay center of the interferometer is set correctly, then a_Q is identically zero. In conventional practice, a_Q is not measured but, in general, $a_U \neq a_L$ and the use of a quadrature correlator permits independent measurements of a_U and a_L with no loss of signal/noise ratio, using the relations:

$$a_U = a_I + a_Q^*$$

$$a_L = a_I - a_Q^*$$

A secondary advantage of this technique is that small delay errors cause only a small phase shift rather than reducing the fringe amplitude as is the case when only the I channel is measured.

This sideband separation is performed to give complex upper and lower sideband fringe amplitudes for all channels. These values are passed to the control computer and stored on disk as one record. A scan, which is typically 5 minutes in length, consists of a consecutive series of records.

Amplitude calibration is done with a standard "chopper" technique (Penzias & Burrus, 1973; Davis and Vanden Bout, 1973) using an ambient temperature absorber which is placed in the beam before each scan. The calculation takes into account the difference in opacity between the two sidebands, and the sideband balance of the receivers, which can be measured directly by using 3-baseline observations of strong point sources. The chopper procedure corrects for receiver gain and atmospheric variations. Finally, daily observations of compact thermal sources (usually Uranus and W3(OH)) are used to determine the absolute flux density scale. Variations between individual correlators are calibrated by measurements of bright quasars (3C84 or 3C273). Since several hours of integration are required to achieve the required signal to noise ratio in each 1MHz channel, these calibrations are performed less often.

Phase calibration is required to correct for the instrumental phase drift, which has a peak to peak amplitude of $\sim 400^\circ$ and is believed to be due to temperature variations in the phase reference system. Bright point sources are observed approximately once every 40 minutes to calibrate the instrumental phase. These sources are typically 0.5-1 radian away from the program sources so the ultimate accuracy of the phase calibration is limited to $15 - 30^\circ$ by the 0.1 λ systematic errors in the baseline determination.

6. Control System

The interferometer is controlled by a distributed computer network in which microcomputers (LSI 11/03) performing various real time tasks are orchestrated by a central computer (PDP 11/40) which also stores the data on its disc. There is one microcomputer in each antenna and one to control the lobe rotator delay lines and data sampling. In addition there is a fifth microcomputer to control the acousto optic spectrometers. A VAX 11/750 is used for off-line data reduction and will eventually replace the PDP 11/40.

The operation of the interferometer is highly automated, with most hardware functions except mechanical tuning of the receivers and Gunn oscillators being controlled by the computers. A versatile 'command file' system can be used to program observing sequences of arbitrary length. In normal operation, the interferometer is programmed to run without operator intervention for 12 or 24 hours, but longer programs are possible. Arithmetic and logical operations are also available in the FORTH command interpreter, permitting the construction of very complex command sequences.

Many hardware alarms are sampled by the computer, with software control of the action to be taken when a fault is detected. A 'deadman' master alarm is wired up to the data taking computer and is triggered when no data have been taken for 15 minutes. This alarm also operates a radio transmitter which triggers a 'beeper' to summon the observer from anywhere on site.

7. Conclusions

In its first season of operation, the Caltech interferometer was used mainly for CO observations of galaxies (Lo *et al.*, 1984) molecular clouds (Masson *et al.*, 1984, Claussen *et al.* 1984) and circumstellar envelopes (Masson *et al.*, 1985, Heiligman *et al.*, in preparation). A similar program was pursued in the second season and the data reduction is now in progress. As an example, Figure 4 shows a map of the integrated CO emission from the active galaxy M82.

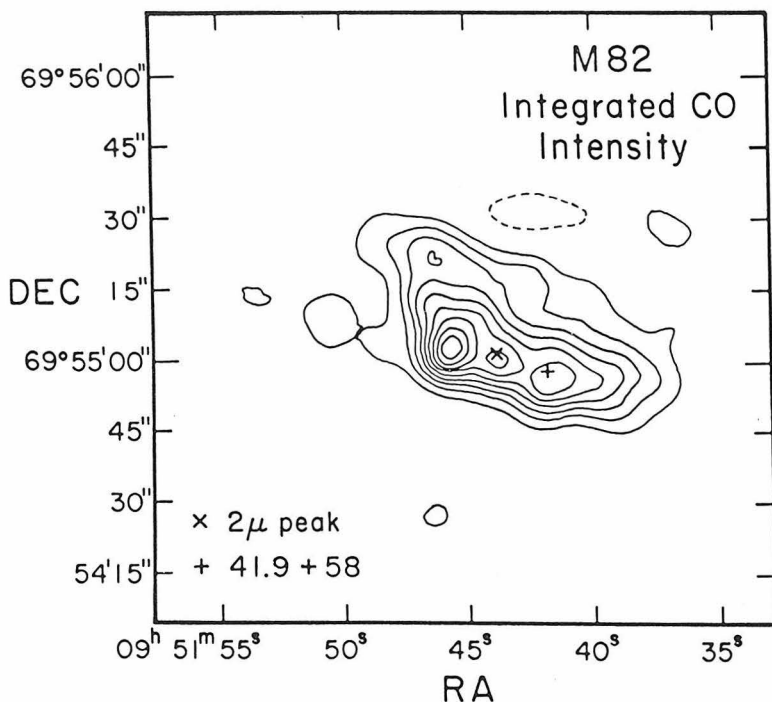


Fig. 4--Map of the integrated CO emission from M82 with 7 arcsec resolution. The x denotes the $2\mu\text{m}$ peak position and the + denotes the radio continuum sources 41.9 + 58.

In addition to interferometry, there has been extensive single-dish work at 1.3mm with studies of galaxies such as M82 (Sutton *et al.* 1983) and detailed line search in OMC1, covering 215-245 GHz (Sutton *et al.* 1985; Blake *et al.*, in preparation and references therein). Several successful VLB experiments at 89GHz have been completed (Readhead *et al.*, 1983) in cooperation with various other observatories.

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